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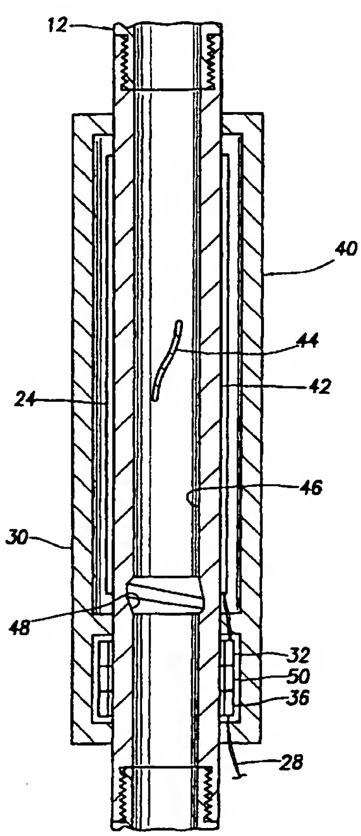
(54) Title: PIEZOELECTRIC DOWNHOLE STRAIN SENSOR AND POWER GENERATOR



(57) **Abstract:** A downhole strain sensor and a power generator provide economy and simplified construction in converting strain in a tubular string into an output downhole. The output may be a signal indicative of strain in the tubular string and/or the output may be electrical power. In a described embodiment, a generally tubular mandrel has a relatively thin layer of piezoelectric material applied thereto, and the mandrel is interconnected in a tubular string. Strain induced in the tubular string is experienced by the mandrel and causes the piezoelectric material to generate an output.

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PIEZOELECTRIC DOWNHOLE STRAIN SENSOR AND POWER GENERATOR

TECHNICAL FIELD

The present invention relates generally to methods and downhole tools used in conjunction with operations in subterranean wells and, in an embodiment described herein, more particularly provides a downhole strain sensor and a power generator.

BACKGROUND

It is generally desirable to be able to communicate with downhole tools in a subterranean well. For example, such communication may be used to convey data and/or instructions to a downhole tool. Additionally, the downhole tool may communicate with a remote location to transmit data regarding pressure, temperature, flow rate, fluid identification, and other information.

It would also be desirable to provide an accurate, economical, reliable and simple method of sensing strain in a tubular string. For example, by sensing strain in a tubular string, pressure or other forces applied to the tubular string may be calculated, a record of the strain in the tubular string may be compiled, the strain in the tubular string may be used to communicate with a downhole tool, etc.

Additionally, it would be very desirable to provide an economical, reliable and simple method of producing electrical power downhole. In this manner, for example, it would not be necessary to run electrical conductors from the earth's surface to a downhole tool to power the tool, nor would it be necessary to rely on batteries charged at the earth's surface and then discharged downhole.

It is accordingly an object of the present invention to provide a downhole strain sensor and a power generator.

SUMMARY

In carrying out the principles of the present invention, in accordance with an embodiment thereof, a downhole strain sensor and a power generator are provided. In a described embodiment, the invention comprises a tubular mandrel to which a layer of piezoelectric material is applied. The piezoelectric material produces an electrical output in response to strain induced in the mandrel.

In one aspect of the present invention, a strain sensor is interconnected as a part of a tubular string positioned in a subterranean well. Strain is induced in the tubular string by, for example, applying pressure to the tubular string, bending the tubular string, applying torque to the tubular string, applying an axial force to the tubular string, etc. The strain in the tubular string is converted into an electrical output by the strain sensor.

In another aspect of the present invention, the strain sensor output may be indicative of data-carrying strain applied to the tubular string. In this manner,

communication may be established between a remote location and a downhole tool interconnected to the strain sensor. For example, data and/or instructions may be transmitted from a remote location to the downhole tool by applying a series of strains to the tubular string. The strain sensor may also include a transmitter for communicating recorded strains in the tubular string to a remote location.

In still another aspect of the present invention, strain induced in a tubular string may be converted into electrical power to be used for operating a downhole tool. The strain in the tubular string causes a piezoelectric material to generate the electrical power. To generate a substantially continuous supply of power, strain may be induced generally continuously in the tubular string, for example, by using fluid flow through the tubular string to cause repeated strain in the tubular string.

These and other features, advantages, benefits and objects of the present invention will become apparent to one of ordinary skill in the art upon careful consideration of the detailed description of representative embodiments of the invention hereinbelow and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic partially cross-sectional view of a method embodying principles of the present invention;

FIG. 2 is a schematic cross-sectional view of a strain sensor embodying principles of the present invention which may be used in the method of FIG. 1; and

FIG. 3 is a schematic partially cross-sectional view of a power generator embodying principles of the present invention which may be used in the method of FIG. 1.

DETAILED DESCRIPTION

Representatively illustrated in FIG. 1 is a method 10 which embodies principles of the present invention. In the following description of the method 10 and other apparatus and methods described herein, directional terms, such as "above", "below", "upper", "lower", etc., are used for convenience in referring to the accompanying drawings. Additionally, it is to be understood that the various embodiments of the present invention described herein may be utilized in various orientations, such as inclined, inverted, horizontal, vertical, etc., without departing from the principles of the present invention.

As depicted in FIG. 1, initial steps of the method 10 have already been performed. A tubular string 12, such as a production tubing string, is positioned in a well. An apparatus 14, which embodies principles of the present invention, is interconnected in the tubular string 12 as a portion thereof. Fluid flow through the tubular string 12, thus, flows through the apparatus 14 also. Specifically, fluids produced from a formation 16 intersected by the well flow into the tubular string 12 via a production valve 18, such as a sliding sleeve valve, and then flow through the tubular string to the earth's surface. However, it is to be clearly understood that the method 10 is merely an example of a method in which principles of the present invention may be incorporated. The apparatus 14 may be interconnected in other types of tubular strings in other types of wells without departing from the principles of the present invention.

Referring additionally now to FIG. 2, a strain sensor 20 embodying principles of the present invention is representatively and schematically illustrated. The sensor 20 may be used for the apparatus 14 in the method 10. Accordingly, the sensor 20 is depicted in FIG. 2 as being interconnected in the tubular string 12, but it is to be clearly understood that it is not necessary for the sensor 20 to be interconnected in the tubular string 12, or for the sensor to be used in the method 10.

The sensor 20 includes a generally tubular mandrel 22 configured for interconnection in the tubular string 12. A relatively thin layer of piezoelectric material 24 is applied to the mandrel 22. The layer of piezoelectric material 24 is relatively thin compared to a wall thickness of the mandrel 22. As depicted in FIG. 2, the layer of piezoelectric material 24 is applied externally to the mandrel 22 and extends continuously about the mandrel, completely circumscribing the mandrel. The piezoelectric material 24 may be a single piece of material, or it may be multiple portions of material. Additionally, the piezoelectric material 24 could be applied to the interior of the mandrel 22, without departing from the principles of the present invention.

The piezoelectric material 24 may be applied to the mandrel 22 using any of a variety of methods. For example, the piezoelectric material 24 may be a film of material adhered to an interior or exterior surface of the mandrel 22, or the piezoelectric material may be a coating applied to the mandrel and then treated to obtain its piezoelectric properties, etc. A suitable piezoelectric material is known as PZT. However, it is to be clearly understood that any type of piezoelectric material may be used for the piezoelectric material 24 in the sensor 20.

It will be readily appreciated by those skilled in the art that, when a strain is applied to the mandrel 22, the piezoelectric material 24 will also experience the strain and will generate an electrical output in response to the strain. Thus, when the sensor 20 is used for the apparatus 14 in the method 10, a torque, axial force, bending moment, pressure, etc. may be applied to the tubular string 12 in order to induce strain in the mandrel 22 and thereby generate an electrical output from the piezoelectric material 24. The electrical output of the piezoelectric material 24 is, therefore, indicative of the strain applied to the mandrel 22.

Any means of inducing a strain in the mandrel 22 may be used in the method 10. Furthermore, a series of strains may be applied to thereby communicate data or instructions to the sensor 20. For example, a series of pressure pulses applied to the tubular string 12 may carry instructions for operation of a downhole tool 26 interconnected via lines 28 to the sensor 14. Communication between a remote

location, such as the earth's surface, and the sensor 20 may also be accomplished by transmitting acoustic signals via the fluid interior or exterior to the tubular string 12, or via the tubular string itself.

Thus, in the method 10, a data- and/or instruction-carrying series of strains may be applied to the tubular string 12 and sensed by the sensor 14, and the data or instructions may be relayed to the tool 26. For example, if the tool 26 is a safety valve, the series of strains applied to the tubular string 12 may carry an instruction for the valve to open or close. This method permits a downhole tool to be controlled from a remote location without the need for wires, control lines, etc. extending between them.

The piezoelectric material 24 is isolated from fluids in the well by a housing or enclosure 30. The housing 30 is attached to the mandrel 22 and outwardly encloses the piezoelectric material 24. Of course, if the piezoelectric material 24 is otherwise positioned relative to the mandrel 22, for example, if the piezoelectric material is internal to the mandrel, the housing 30 may be differently positioned and attached to the mandrel as well.

The sensor 20 further includes electrical and/or electronic devices which enable and/or enhance its operation in specific applications. As depicted in FIG. 2, the sensor 20 includes a signal conditioning device 32, a memory device 34 and a communication device 36. The signal conditioning device 32 receives the output of the piezoelectric material 24 and places it in a usable form, for example, by impedance matching, amplification, etc. The memory device 34 records the output of the piezoelectric material 24 for later retrieval or for transmission to a remote location.

The communication device 36 transmits the output of the piezoelectric material 24 to another location, either in real time or from the stored output in the memory device 34. For example, the communication device 36 as depicted in FIG. 1 is connected to the lines 28, which are also connected to the tool 26, whereby the sensor 20 is in communication with the tool 26. It will be readily appreciated that

other means of communication, such as acoustic telemetry, mud pulse telemetry, electromagnetic telemetry, etc., may be used in the communication device 36, and the communication device may communicate with any other location, such as the earth's surface or another location in the well, without departing from the principles of the present invention.

Referring additionally now to FIG. 3, a power generator 40 embodying principles of the present invention is representatively and schematically illustrated. The power generator 40 may be used for the apparatus 14 in the method 10, and may also be used in other methods in keeping with the principles of the present invention. The power generator 40 is similar in many respects to the strain sensor 20 described above, and elements shown in FIG. 3 which are similar to those previously described are indicated using the same reference numbers.

As depicted in FIG. 3, the power generator 40 is interconnected in the tubular string 12 in the method 10. However, it is to be clearly understood that the power generator 40 may be interconnected in other types of tubular strings, without departing from the principles of the present invention.

Similar to that described above for the sensor 20, a strain induced in the tubular string 12 will also be experienced by a generally tubular mandrel 42 of the power generator 40. The mandrel 42 is in most respects similar to the mandrel 22 of the strain sensor 20. However, the mandrel 42 may include other features which act to induce strain in the mandrel and, therefore, generate an output of the piezoelectric material 24.

The mandrel 42 has a flow deflector 44 in an internal flow passage 46 that is in communication with the interior of the tubular string 12. The flow deflector 44 as depicted in FIG. 3 is somewhat fin-shaped and acts to create turbulence, or a change in fluid momentum, in the fluid flow through the passage 46. If, as in the method 10, the tubular string 12 is a production tubing string, it will be appreciated that there is substantially continuous fluid flow through the passage. This means that the flow detector 44 is substantially continuously creating turbulence or momentum change

in the fluid flow. Alternatively, or in addition to the flow deflector 44, the mandrel 42 may have an internal profile 48 formed therein to create turbulence in the fluid flow. The profile 48 may be asymmetrical as shown in FIG. 3 to thereby enhance its turbulence or momentum change creating feature. It is, however, to be clearly understood that any means, or no means, of creating turbulence or momentum change in the fluid flow through the passage 46 may be utilized in keeping with the principles of the present invention.

It will be readily appreciated by those skilled in the art that, with the deflector 44, profile 48 or other means creating turbulence or momentum change in the fluid flow through the passage 46, the turbulence or momentum change induces strain in the mandrel 42, thereby causing the piezoelectric material 24 to generate an electrical output. Therefore, by creating substantially continuous turbulence or momentum change in the fluid flow through the passage 46, a substantially continuous generation of electrical output may be had from the piezoelectric material 24. Thus, it is not necessary for the strain which causes an electrical output from the piezoelectric material 24 to be applied to the tubular string 12 at the earth's surface, although strain may be applied to the tubular string 12 to generate an electrical output of the piezoelectric material 24, if desired, as with the sensor 20 described above.

The power generator 40 includes the signal conditioning device 32 and communication device 36, and also includes a battery or other energy storage device 50 for storing the electrical output of the piezoelectric material 24. For example, the signal conditioner 32 may take a substantially continuous AC-type electrical output of the piezoelectric material 24 and convert it to a DC current suitable for charging the battery 50 The electrical power stored in the battery 50 may then be used to operate a downhole tool, such as the tool 26 in the method 10, using the communication device 36 to convert the battery output so that the tool 26 may be operated thereby. For example, the tool 26 may require AC power for its operation, in which case the device 36 may convert the DC output of the battery 50 to an AC

output. Of course, the communication device 36 may communicate in other manners with remote locations as described above for the sensor 20.

It may now be fully appreciated that the principles of the present invention provide methods whereby strain in a tubular string may be easily, simply and economically generated, sensed, recorded, transmitted, used to generate power, used to operate a downhole tool and/or used to communicate with remote locations. It will also be readily appreciated that features of the sensor 20 and power generator 40 may be easily combined. For example, the sensor 20 may include the battery 50, the flow deflector 44 and/or the profile 48 of the power generator 40, and the power generator 40 may include the memory device 34 of the sensor 20. Thus, a combined sensor/power generator may be conveniently constructed using the above described principles of the present invention.

Of course, a person skilled in the art would, upon a careful consideration of the above description of representative embodiments of the invention, readily appreciate that many modifications, additions, substitutions, deletions, and other changes may be made to these specific embodiments, and such changes are contemplated by the principles of the present invention. Accordingly, the foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the present invention being limited solely by the appended claims.

WHAT IS CLAIMED IS:

1. A method of sensing strain in a tubular string in a subterranean well, the method comprising the steps of:

applying a relatively thin layer of a piezoelectric material to a generally tubular mandrel;

interconnecting the mandrel in the tubular string;

positioning the tubular string including the mandrel in the well; and

inducing a strain in the tubular string proximate the mandrel, the piezoelectric material thereby producing an output indicative of the strain.

2. The method according to Claim 1, wherein the applying step further comprises adhering a film of the piezoelectric material to the mandrel.

3. The method according to Claim 1, wherein the applying step further comprises coating the mandrel with the piezoelectric material.

4. The method according to Claim 1, wherein in the applying step, the piezoelectric material is applied as a single continuous layer to the mandrel.

5. The method according to Claim 1, wherein in the applying step, the piezoelectric material is applied in multiple portions to the mandrel.

6. The method according to Claim 1, wherein in the applying step, the piezoelectric material is applied externally to the mandrel.

7. The method according to Claim 1, further comprising the step of enclosing the piezoelectric material within an enclosure attached to the mandrel, the enclosure isolating the piezoelectric material from contact with well fluids in the positioning and strain inducing steps.

8. The method according to Claim 1, wherein the strain inducing step is performed by applying an axial force to the tubular string.

9. The method according to Claim 1, wherein the strain inducing step is performed by applying a torque to the tubular string.

10. The method according to Claim 1, wherein the strain inducing step is performed by applying a pressure to the tubular string.

11. The method according to Claim 1, wherein the strain inducing step is performed by applying a bending moment to the tubular string.

12. The method according to Claim 1, wherein the strain inducing step is performed by transmitting an acoustic signal from a remote location via fluid in contact with the tubular string.

13. The method according to Claim 1, wherein the strain inducing step is performed by transmitting an acoustic signal from a remote location via the tubular string.

14. The method according to Claim 1, further comprising the step of storing in a downhole memory a record of the strain indication output by the piezoelectric material.

15. The method according to Claim 1, further comprising the step of transmitting to a remote location the strain indication output by the piezoelectric material.

16. The method according to Claim 1, wherein in the strain inducing step, the strain induced in the tubular string is a series of data-carrying strains, the output thereby containing data transmitted from a remote location.

17. The method according to Claim 1, wherein in the strain inducing step, the strain induced in the tubular string is a series of instruction-carrying strains, the output thereby containing instructions transmitted from a remote location.

18. The method according to Claim 17, further comprising the steps of interconnecting a downhole tool to the output of the piezoelectric material, and controlling the operation of the tool by the instructions transmitted from the remote location.

19. A method of producing power from strain in a tubular string in a subterranean well, the method comprising the steps of:

applying a relatively thin layer of a piezoelectric material to a generally tubular mandrel;

interconnecting the mandrel in the tubular string;

positioning the tubular string including the mandrel in the well; and

inducing a strain in the tubular string proximate the mandrel, the piezoelectric material thereby producing electric power in response to the strain.

20. The method according to Claim 19, wherein the inducing step is performed by flowing fluid through the mandrel.

21. The method according to Claim 20, wherein the inducing step further comprises creating a change in momentum in the fluid flowing through the mandrel.

22. The method according to Claim 20, wherein the inducing step further comprises creating turbulence in the fluid flowing through the mandrel.

23. The method according to Claim 22, wherein the turbulence creating step is performed by forming an internal profile in the tubular string.

24. The method according to Claim 23, wherein the forming step further comprises forming the profile asymmetrically.

25. The method according to Claim 22, wherein the turbulence creating step is performed by positioning a flow deflector within the tubular string.

26. The method according to Claim 19, wherein the applying step further comprises adhering a film of the piezoelectric material to the mandrel.

27. The method according to Claim 19, wherein the applying step further comprises coating the mandrel with the piezoelectric material.

28. The method according to Claim 19, wherein in the applying step, the piezoelectric material is applied as a single continuous layer to the mandrel.

29. The method according to Claim 19, wherein in the applying step, the piezoelectric material is applied in multiple portions to the mandrel.

30. The method according to Claim 19, wherein in the applying step, the piezoelectric material is applied externally to the mandrel.

31. The method according to Claim 19, further comprising the step of enclosing the piezoelectric material within an enclosure attached to the mandrel, the enclosure isolating the piezoelectric material from contact with well fluids in the positioning and strain inducing steps.

32. The method according to Claim 19, wherein the strain inducing step is performed by applying an axial force to the tubular string.

33. The method according to Claim 19, wherein the strain inducing step is performed by applying a torque to the tubular string.

34. The method according to Claim 19, wherein the strain inducing step is performed by applying a pressure to the tubular string.

35. The method according to Claim 34, wherein the pressure is applied to the tubular string as a predetermined series of pulses, thereby producing a corresponding alternating current output of the piezoelectric material.

36. The method according to Claim 19, wherein the strain inducing step is performed by applying a bending moment to the tubular string.

37. The method according to Claim 19, further comprising the step of storing in a downhole battery the electric power output by the piezoelectric material.

38. The method according to Claim 19, further comprising the step of operating a downhole tool using the electric power output by the piezoelectric material.

39. A downhole strain sensor for interconnection in a tubular string in a subterranean well, the strain sensor comprising:

a generally tubular mandrel interconnectable in the tubular string; and

a layer of a piezoelectric material applied to the mandrel, the piezoelectric material producing an output in response to a strain induced in the mandrel.

40. The strain sensor according to Claim 39, further comprising a memory device interconnected to the piezoelectric material, the memory device storing therein the piezoelectric material output.

41. The strain sensor according to Claim 39, further comprising a transmitter interconnected to the piezoelectric material, the transmitter transmitting the piezoelectric material output to a remote location.

42. The strain sensor according to Claim 39, wherein the piezoelectric material layer is relatively thin compared to a wall thickness of the mandrel.

43. The strain sensor according to Claim 39, wherein the piezoelectric material layer is a film adhered to the mandrel.

44. The strain sensor according to Claim 39, wherein the piezoelectric material layer is a coating on the mandrel.

45. The strain sensor according to Claim 39, wherein the piezoelectric material layer is a single continuous layer on the mandrel.

46. The strain sensor according to Claim 39, wherein the piezoelectric material layer comprises multiple portions on the mandrel.

47. The strain sensor according to Claim 39, wherein the piezoelectric material layer is external to the mandrel.

48. The strain sensor according to Claim 39, further comprising an enclosure isolating the piezoelectric material from contact with fluids about the mandrel.

49. A downhole power generator for interconnection in a tubular string in a subterranean well, the power generator comprising:

a generally tubular mandrel interconnectable in the tubular string; and

a layer of a piezoelectric material applied to the mandrel, the piezoelectric material producing electrical power in response to a strain induced in the mandrel.

50. The power generator according to Claim 49, further comprising a battery interconnected to the piezoelectric material, the battery storing electrical power produced by the piezoelectric material.

51. The power generator according to Claim 49, wherein the piezoelectric material layer is relatively thin compared to a wall thickness of the mandrel.

52. The strain sensor according to Claim 49, wherein the piezoelectric material layer is a film adhered to the mandrel.

53. The strain sensor according to Claim 49, wherein the piezoelectric material layer is a coating on the mandrel.

54. The strain sensor according to Claim 49, wherein the piezoelectric material layer is a single continuous layer on the mandrel.

55. The strain sensor according to Claim 49, wherein the piezoelectric material layer comprises multiple portions on the mandrel.

56. The strain sensor according to Claim 49, wherein the piezoelectric material layer is external to the mandrel.

57. The strain sensor according to Claim 49, further comprising an enclosure isolating the piezoelectric material from contact with fluids about the mandrel.

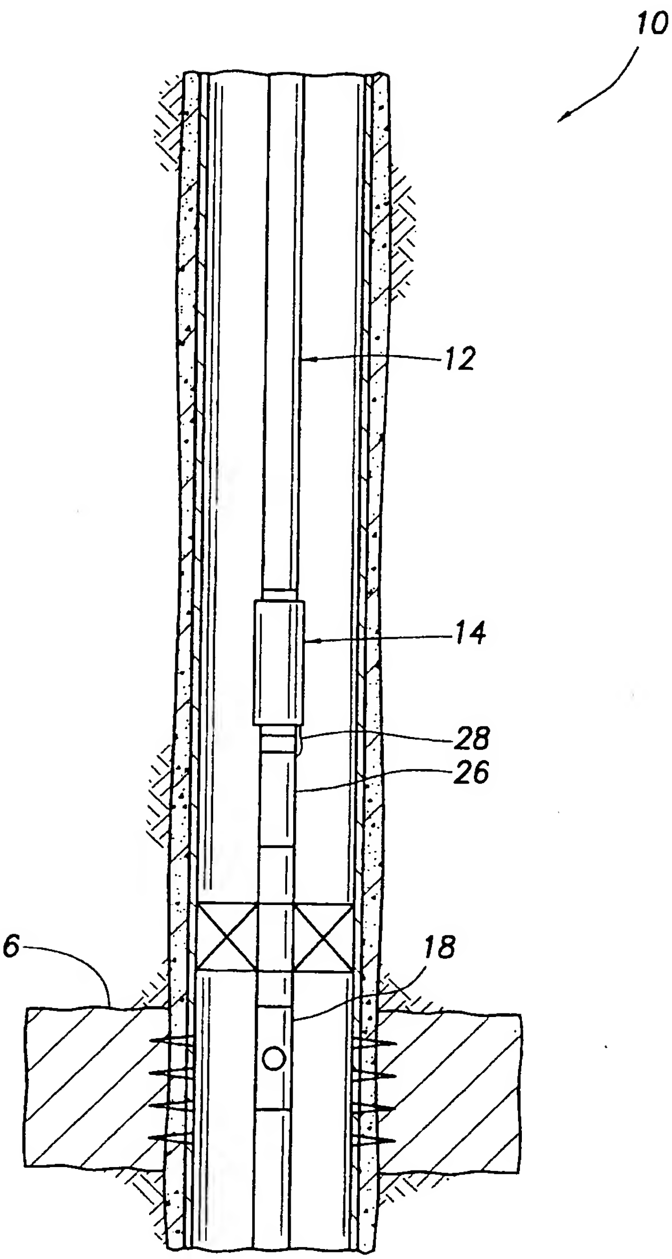

FIG. 1

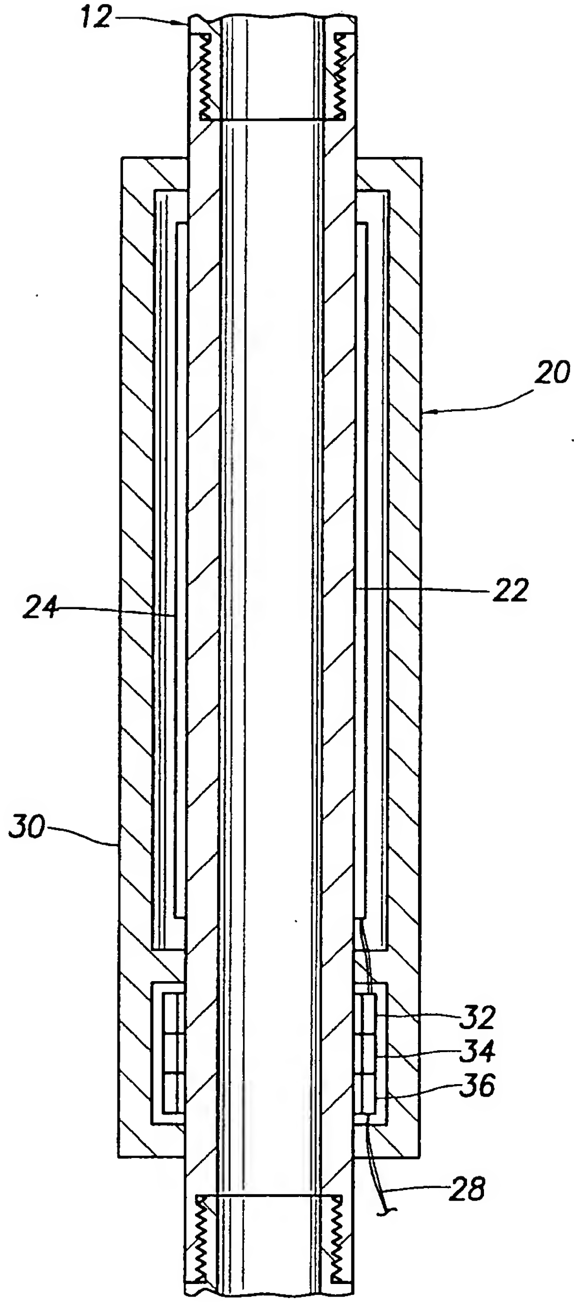

FIG.2

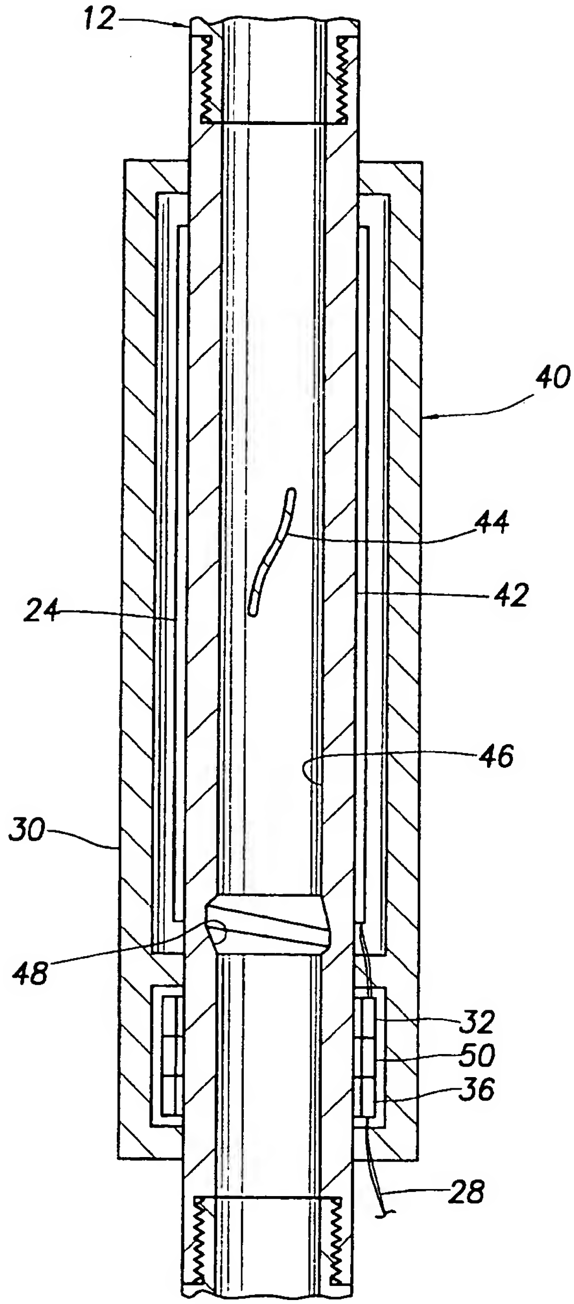

FIG.3

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/31621

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L41/113 E21B41/00 E21B47/00 E21B47/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 970 877 A (RUSSELL MICHAEL KING ET AL) 20 July 1976 (1976-07-20) column 1, line 28-40; figure 1	19-26, 28-30
Y	column 2, line 12-19	1-18,27, 31-36, 39-48, 53,54, 56,57
X	US 5 839 508 A (ROSS ROBERT CHAPMAN ET AL) 24 November 1998 (1998-11-24) column 9, line 42 -column 10, line 10; figures 5,11	19-26, 29,37, 38, 49-52,55

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
2 February 2001	08/02/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	van Berlo, A

4

INTERNATIONAL SEARCH REPORT

International Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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	column 6, line 3-22 column 7, line 39-43; figures 1-5 column 7, line 10-27	
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Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

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